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# Application of in situ direct shear device to shear strength measurement of rockfill materials

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***Abstract:*** A simplified in situ direct shear test (DST) was developed for measuring the shear strength of soils in fields. In this test, a latticed shearing frame replaces the upper half of the shear box used in the conventional direct shear box test. The latticed shearing frame is directly embedded in the ground to be tested after a construction process and is pulled with a flexible chain while a constant dead load is applied to the sample in the shearing frame. This simplified in situ DST has been validated by comparing its results with those of triaxial tests on samples with parallel gradations under normal stresses less than 100 kPa. In this study, the DST was further validated by carrying out tests on samples with the same gradations, rather than on samples with parallel gradations, under normal stresses up to 880 kPa. In addition, the DST was performed inside fills in two applications.

***Key words:*** *in situ; direct shear test; shear strength; rockfill*

## 1 Introduction

The DST is one of the most popular laboratory tests for directly determining the Mohr-Coulomb strength envelope of geo-material because of its time efficiency in shearing and easy operation. In a DST, the shear deformation is nearly of plane strain, as occurs in many field problems, and the measured shear strength is nearly an average one along a circular slip plane, as shown in Fig. 1. In a conventional DST (Fig. 2), samples are usually sheared by mobilizing the lower half of the shear box horizontally while the upper half of the shear box is fixed (Skempton and Bishop 1950; Shibuya et al. 1997; Thornton 2000; Lings and Dietz 2004). The shear force is measured with a bearing ring or a load cell that is attached to the upper half of the shear box. In a conventional DST, a friction force is generated at the attachment point when the volume of the sheared sample changes (dilates or contracts). This friction force at the attachment point restrains the upward or downward movement of the upper half of the shear box. Consequently, a friction force between the inside surface of the upper half of the shear box is generated when the volume of the sheared sample changes (dilates or contracts). Owing to

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this interface friction in a conventional DST, the shear strength is generally overestimated for dilatant specimens (like coarse granular soils) but underestimated for contractive ones, as reported by Takada et al. (1996) and Sumi et al. (1997). To minimize this defect, a simplified in situ direct shear testing method has been developed and verified within a relatively low range of normal stresses (<100 kPa) through comparison with triaxial compression tests on specimens with parallel gradations, in which the size distributions are almost parallel to those of the field material because the maximum particle size of the field material is reduced to what can be handled in the laboratory (Matsuoka and Liu 1998; Liu 1999; Matsuoka et al. 2001; Liu et al. 2005; Liu 2006).

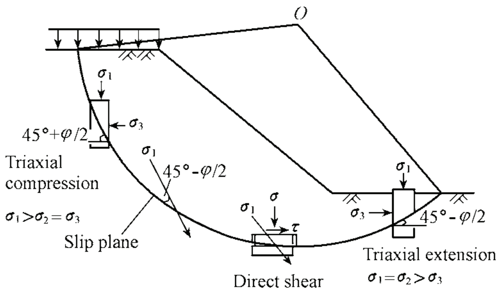



**Fig. 1** DST approximately simulating average stress conditions along circular slip plane

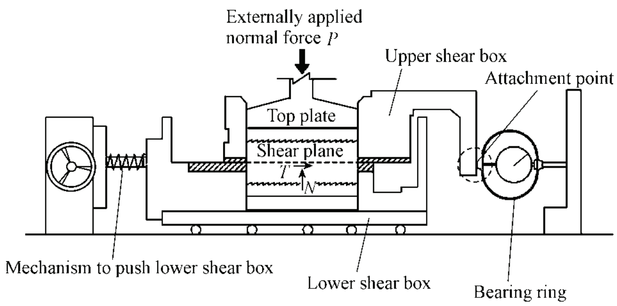



**Fig. 2** Schematic diagram of conventional direct shear box test device

This paper presents further validation of the simplified in situ DST through comparison with triaxial compression tests on specimens with the same gradations (rather than parallel gradations) across a wide range of normal stress levels, and provides some results for compacted rockfill materials. In general, a rockfill dam or embankment is built in layers, with each layer (lift) commonly 80cm to 100 cm thick and compacted on the surface. This construction procedure results in different distributions of compaction density. The shear strength of the rockfill within a lift is higher near the top surface of the lift than at the bottom. The in situ DST allows for the measurement of shear strength at any depth within the lift. Two such applications are presented in this paper.

## 2 Simplified in situ DST

The simplified in situ DST has been detailed by Liu (1999) and Matsuoka et al. (2001), and its sketch is shown in Fig. 3. In the simplified in situ DST, a latticed shearing frame, which is equivalent to the upper half of the shear box in the conventional DST and made of high-strength steel, is buried in the ground to be tested, and then is compacted in the same way it would be in the real construction process. Several latticed shearing frames with different sizes are prepared for testing materials with different grain sizes. For coarse-grained rockfill, a latticed shearing frame with a size of 122.5 cm × 122.5 cm × 16 cm is usually used. For gravel or sandy soils, the latticed shearing frame can be reduced to 63.2 cm × 63.2 cm (area: 4 000 $cm^2$) × 16 cm or 31.6 cm × 31.6 cm (area: 1 000 $cm^2$) × 10 cm. The shearing frame is pulled horizontally with a flexible chain attached to a heavy machine (e.g., a bulldozer) through an oil jack while a constant vertical (normal) force is applied. The shear force is measured with a load cell that is contained in the hollow center of the oil jack.

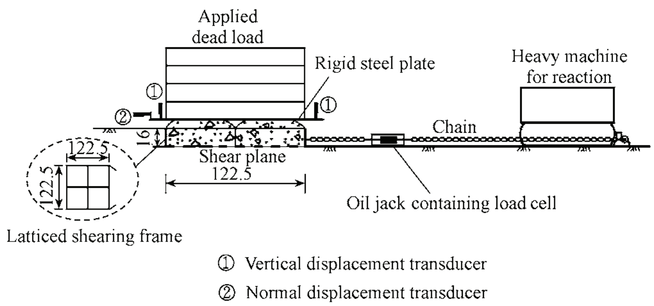



**Fig. 3** Sketch of simplified in situ DST (Unit: cm)

The forces acting on the specimen in the simplified in situ DST are illustrated in Fig. 4 (for the sake of simplicity, only one mesh of the latticed shearing frame is illustrated). The equilibrium of the forces gives the following equations:

$$N = P + W + W_1 + W_2 - P_1 \tag{1}$$

$$T = F - F_1 \tag{2}$$

$$\sigma = N/A, \quad \tau = T/A \tag{3}$$

where $T$ is the shear force along the shear plane; $N$ is the true normal force on the shear plane; $P$ is the externally applied force on the top plate in the normal direction (usually recorded during the test); $F$ is the shear force measured with the load cell; $W$ is the dead weight of the specimen inside the shearing frame, $W_1$ and $W_2$ are the dead weights of the shearing frame and the loading plate, respectively; $F_1$ and $P_1$ are the frictional and vertically supportive forces on the contact plane between the shearing frame and the specimen, respectively; $A$ is the area of the shear plane (shearing frame); and $\sigma$ and $\tau$ are the normal and shear stresses on the shear plane, respectively. In the above equations, $P$, $W$, $W_1$, $W_2$, $A$ and $F$ are measurable, while $P_1$ and $F_1$ are close to zero and may be neglected since the vertical force is not applied directly to the ribs of the shearing frame and the shearing frame nearly floats above the shear plane when the sample dilates. As a result, the true stresses $\sigma$ and $\tau$ on the shear plane are more accurately measured in this simplified in situ DST, especially for granular materials that dilate prior to the peak stress. In addition, to minimize the moment caused by the horizontal force $F$, the chain should be connected to the shearing frame as near to the shear plane as possible. To date, the maximum tilting angle of the shearing frame prior to peak strength is 0.8° (Matsuoka and Liu 1998; Matsuoka et al. 2001), showing that the shearing frame remains almost horizontal during the shearing process.

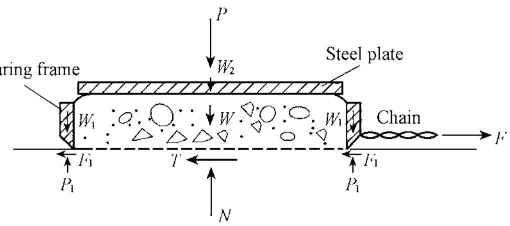



**Fig. 4** Force analysis of simplified in situ DST

# 3 Validation of simplified DST

## 3.1 Laboratory DSTs

A DST apparatus that has the same principle as the simplified in situ DST was conducted in the laboratory (Fig. 5). In the laboratory apparatus, the normal and shear forces were applied through two oil cylinders, each having a loading capacity of 98 kN. The specimen was contained in a 140 cm × 140 cm × 60 cm steel box. Comparative DSTs were performed both in the laboratory and in situ on rockfill material with the same initial void ratio ( $e_0 = 0.37$ ) and normal stresses. Fig. 6 compares the measured peak shear strengths between in situ and laboratory DSTs, and Fig. 7 shows the relationships between the shear-normal stress ratio and the horizontal (shear) displacement, and the relationships between the vertical (normal) displacement and the horizontal displacement. Good agreement can be seen both for the measured peak shear strengths, and the stress ratio-displacement relationships.

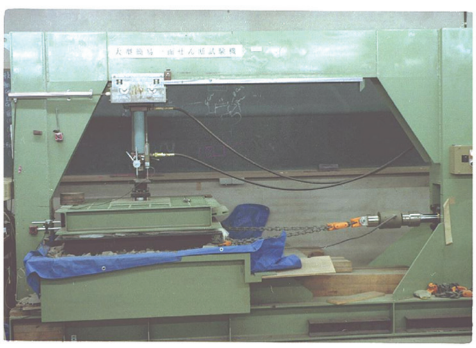


**Fig. 5** New laboratory DST apparatus

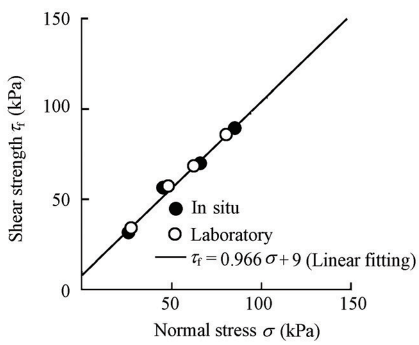



**Fig. 6** Comparison between measured shear strengths of in situ and laboratory DSTs

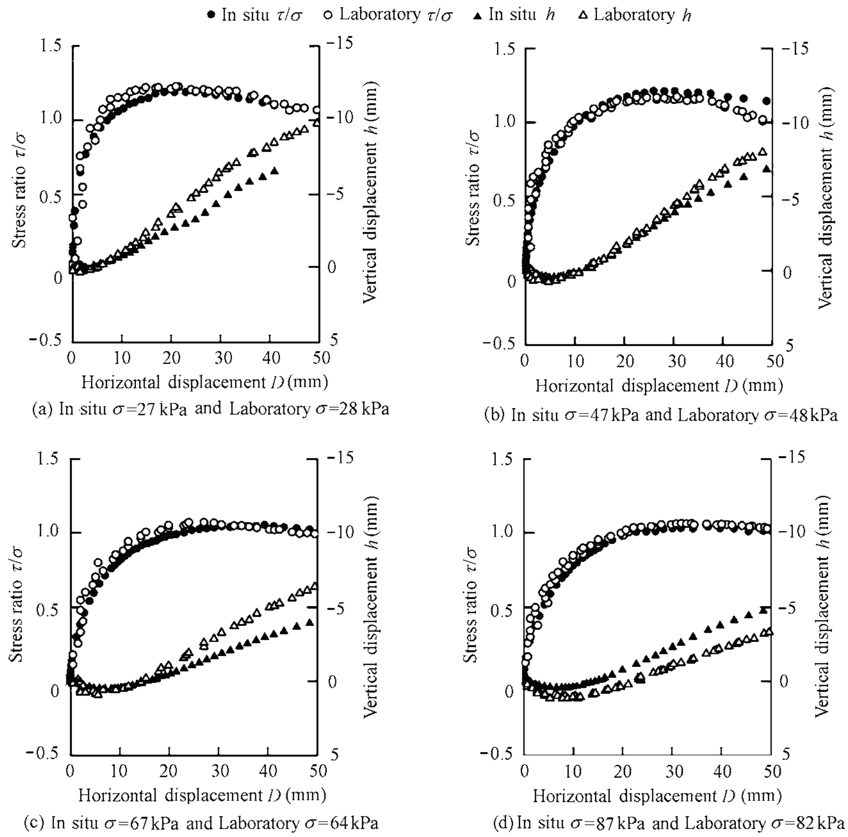



**Fig. 7** Comparison between stress ratio-displacement relations of in situ and laboratory DSTs under different normal stresses

## 3.2 Large-scale triaxial compression tests

The simplified in situ DST was verified within a relatively low range of applied normal stresses through comparison with triaxial compression tests on parallel gradation samples (Liu 1999; Matsuoka and Liu 1998; Matsuoka et al. 2001). In this study, further validation using samples with the same gradation (rather than parallel gradation) was undertaken across a higher range of applied normal stresses (Liu et al. 2003). Two rockfill materials with particle diameters corresponding to the tenth percentile of accumulative volume $d_{10}$ = 0.11 mm, referred to as sample LS and sample MS, were used for the validation. Sample LS was crushed limestone while sample MS was a composite of crushed sandstone and other rock. As the specimen in triaxial tests was 30 cm in diameter, the maximum grain size $D_{max}$ of the tested materials was adjusted to be 53 mm according to the specification of Japanese Society of Soil Mechanics and Foundation Engineering (1982) that the triaxial specimen should not contain grains larger than 0.15 to 0.2 times the size of the specimen. The shearing frames had to be scaled down to achieve higher normal stresses. In this study, two small shearing frames with sizes of 31.6 cm × 31.6 cm × 4 cm and 60 cm × 60 cm × 10 cm were used. The specimen box in the laboratory DST apparatus was narrowed using wooden blocks of 45 cm × 55 cm × 30 cm for the 31.6 cm × 31.6 cm × 4 cm shearing frame, and 80 cm × 80 cm × 21 cm for the 60 cm × 60 cm × 10 cm shearing frame. When the applied normal stress was greater than 500 kPa, the 31.6 cm × 31.6 cm × 4 cm shearing frame was used; otherwise, the 60 cm × 60 cm × 10 cm shearing frame was used.

Simplified direct shear and triaxial compression tests were conducted on samples LS and MS with the same maximum grain size of 53 mm in two independent laboratories. The initial dry densities $\rho_t$ were, respectively, 2.10 g/cm$^3$ for sample LS and 1.92 g/cm$^3$ for sample MS. The maximum normal stress applied in the simplified DSTs was 683 kPa for sample LS and 880 kPa for sample MS. Fig. 8 shows the test results with respect to the peak shear strengths against the applied normal stresses. It can be seen that, even at higher normal stresses, the peak shear strength envelopes for both LS and MS samples obtained from the simplified DSTs are consistent with the Mohr's stress circles at failure obtained from the triaxial compression tests. Theoretically, the shear strength in a DST is somewhat higher than that of a triaxial test because of stress-strain conditions. This tendency is vaguely evident for sample MS in Fig. 8(b).

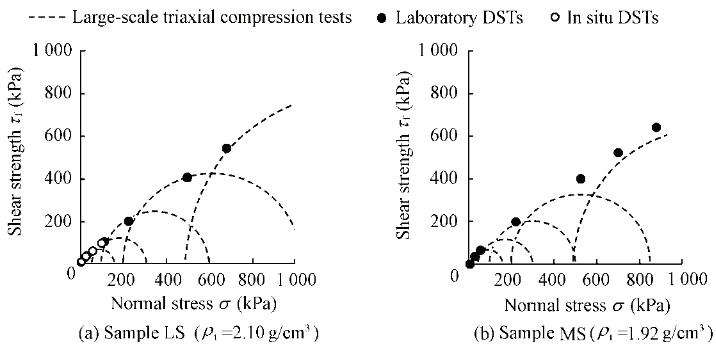



**Fig. 8** Comparison between shear strengths of rockfill material of simplified DSTs and triaxial compression tests under high normal stress

The in situ DST was also performed on sample LS. The used shearing frames were 122.5 cm × 122.5 cm × 16 cm, and the normal stresses applied were 3.0 kPa, 23 kPa, 52 kPa and 101 kPa. The measured peak shear strengths, plotted together in Fig. 8(a), correspond reasonably with those obtained from the laboratory DSTs regardless of the different sizes of the used shearing frames. It has previously been shown that the size of the shearing frame hardly affects the measured shear strengths when the shearing frame is more than four or five times the maximum grain size of the specimen tested (Matsuoka et al. 2001).

It is noted from Fig. 8 that the normal stresses applied to the shear plane in the simplified DST can be less than 5.0 kPa, due to the dead weight of the shearing frame and the contained specimen. The shear strengths under such low normal stresses are required in the analysis of slope stability of rockfill dams where shallow failures take place. As illustrated in Fig. 8, the measured shear strength envelopes for both LS and MS pass through the origin, suggesting that there exist no real cohesions for coarse granular materials.

# 4 Tests on rockfill materials

## 4.1 Tests on surface of compacted layers

Matsuoka et al. (2001) provided results from simplified in situ DSTs on eight rockfill materials. Fig. 9 presents the results for another three rockfill materials, samples LS, MS and LC, with maximum grain sizes $D_{max}$ = 200 mm. The shearing frames were 122.5 cm × 122.5cm × 16 cm. Samples LS and MS were used in the laboratory validation tests described above after being adjusted so as to have parallel gradations with $D_{max}$ = 53 mm. The sample LS was tested at two initial dry densities. As shown in Fig. 9(a), the measured shear strengths increase along with the dry density. Fig. 10 shows the tests at a pumped-storage power station construction field in China (Liu et al. 2004). The tested rockfill material had a maximum grain size of 300 mm and an average grain size of 40 mm. Since the applied normal stress was expected to reach 260 kPa in this field, a concrete pier was cast to act as the reaction for the pulling force.

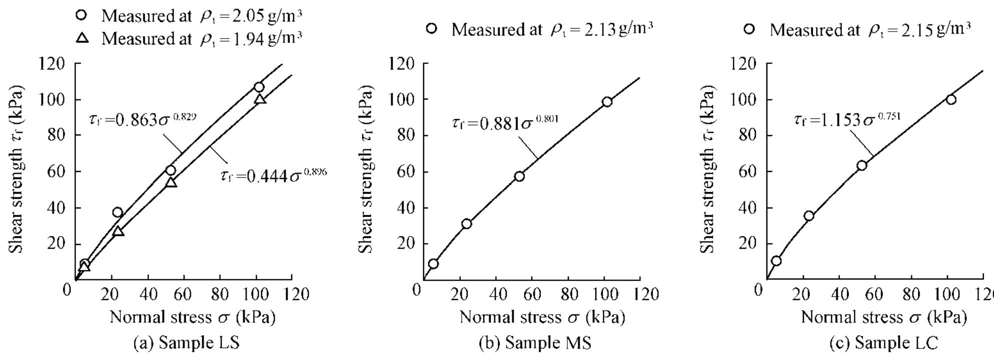



**Fig. 9** Results of simplified in situ DSTs on rockfill material with $D_{max}$ = 200 mm performed on ground surface

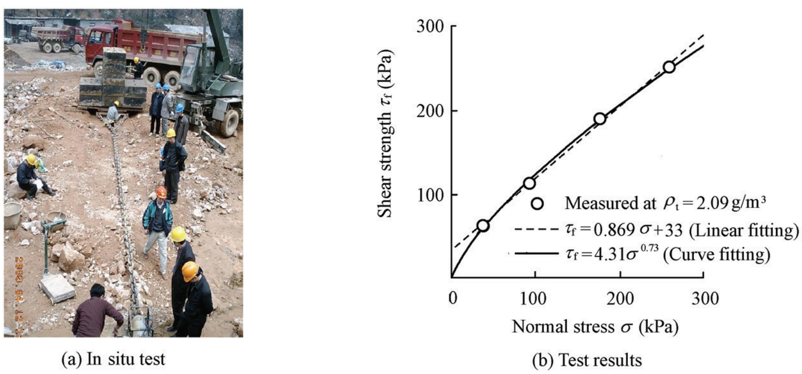


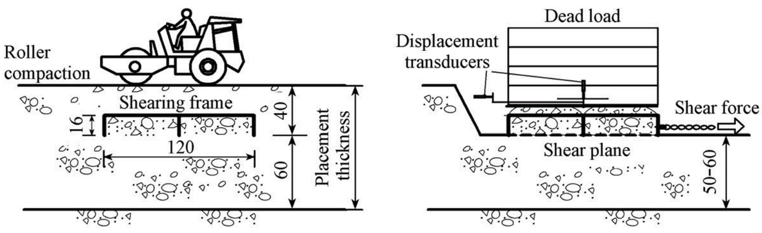

**Fig. 10** Results of simplified in situ DSTs on rockfill material with

$D_{max}$ = 300 mm performed on ground surface

## 4.2 Tests inside compacted layers

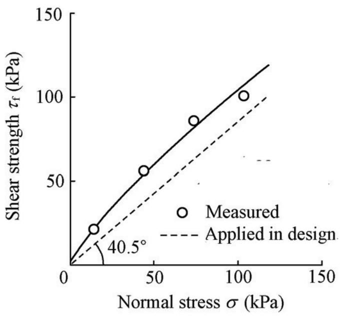
Typically, rockfill dams and embankments are constructed in compacted layers, with each lift layer being 0.8-1.0 m thick and compacted by vibratory rollers on the surface. Since the compaction energy decreases with depth inside the lift, the in-place density and, correspondingly, the shear strength of rockfill, are not uniform within the lift. The distribution of the shear strength along the lift can be determined by the simplified in situ DST.

Fig. 11 shows a schematic view of the simplified in situ DST performed inside a lift (1 m thick) in a dam construction field. The shearing frames were embedded inside the lift during the rockfill placement. After compaction on the surface, the material above the shearing frame was removed carefully and the tests were carried out in the same way as on the compacted surface (Fig. 11(b) and Fig. 12(a)). As shown in Fig. 12(b), the measured peak shear strength envelope (solid line) is higher than the one adopted in the design (dashed line).




(a) Compaction on lift surface (b) DST inside lift

**Fig. 11** Schematic view of simplified in situ DST performed in middle of lift layer in dam (Unit: cm)

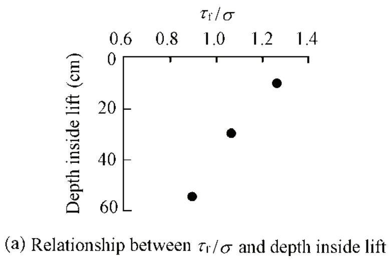



(a) In situ test (b) Test results

**Fig. 12** Shear strength of rockfill ($D_{max}$ = 200 mm) from in situ DST performed in middle of lift layer in dam

Fig. 13 presents another simplified in situ DST performed inside the lift in a highway embankment construction field. Each lift in this field was 60 cm thick. The material filled in the embankment had a mean particle size of 2 mm and a maximum particle size of 20 mm. During the placement, three 63.2 cm × 63.2 cm × 8 cm latticed shearing frames were embedded, at 5 cm, 30 cm, and 50 cm above the bottom of the lift. After compaction on the surface of the lift, the material above the top shearing frame was first removed and then tested in the same way as on the fill surface. The same procedures were sequentially carried out for the middle and the lowest shearing frames. As expected, the highest measured shear strength was at the top, and it decreased from the top to the bottom of the lift.

Additionally, it is suggested that the simplified in situ DST may be applied to control the construction quality of rockfill as well. The present practice is to control the construction quality of rockfill according to dry densities that are measured on the compacted surface. This is clearly an indirect approach that overestimates the shear strength of the rockfill in the lift.



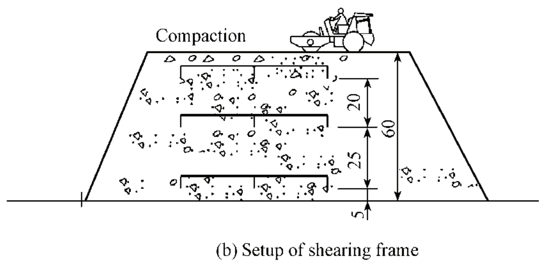




**Fig. 13** Variation of ratio of shear strengths to normal stress of rockfill along depth inside lift measured by simplified in situ DST in embankment

## 5 Conclusions

The simplified in situ DST developed by Liu and Matsuoka (Liu 1999; Matsuoka et al. 2001) is a field technique used to directly determine shear strengths of soils. The simple test is performed by horizontally pulling a shearing frame, embedded in the ground, with a flexible chain under the application of a dead load (normal force). Analysis of the specimen forces indicates that the true normal and shear forces on the shear plane in the simplified DST can be accurately determined. Many validations for the simplified DST have been carried out by comparison with triaxial compression tests across a large range of normal stress levels (up to 880 kPa). For rockfill dams or embankments, the simplified in situ DST can be carried out not only on the fill surface, but also inside the fill lift, enabling the variation of the shear strengths of rockfill along the fill lift to be determined.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